

MCFM and $p\bar{p} \rightarrow W + 2 \text{ jets}$
at next-to-leading order

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Overview

- MCFM and NLO programs
- Details of MCFM
- $Wb\bar{b}$ and $Zb\bar{b}$ as backgrounds to a Higgs signal
- Implementation of $W + 2$ jets
- Conclusions



MCFM Background

- The Tevatron Run II will be sensitive to processes at the femtobarn level.
- Particularly interesting are final states involving heavy quarks, leptons and missing energy.
- MCFM aims to provide a unified description of such processes at NLO accuracy.
- The extension to NLO is made possible in many cases by the recent calculations of virtual matrix elements involving a vector boson and four partons.
- Similar philosophy, but different approach to Pythia. Whilst Pythia has the advantages of extra radiation (partially included in a NLO calculation) and showering, a fixed order MC may be viewed as theoretically cleaner.
- MCFM version 2.0 is now part of the CDF code repository. Working with experimenters to produce user-friendly input and output, e.g. event ntuples rather than just histograms.



Fixed-order QCD Simulations

There are a variety of next-to-leading order Monte Carlo's available for different hadron-hadron processes:

- **Diboson production**, e.g. $p\bar{p} \rightarrow W^+W^- \rightarrow \text{leptons}$.
 - **Baur et al.** - lepton correlations only partially included
Ohnemus, 1994
Baur, Han and Ohnemus, 1995, 1996
 - **Dixon et al.** - full correlations, anomalous couplings
Dixon, Kunszt and Signer, 1999
 - **MCFM** - full correlations, singly-resonant contributions
JC and Ellis, 1999
- **Inclusive jets**, $p\bar{p} \rightarrow$ at least n jets.
 - **JETRAD** - 1 and 2 jets only
Giele, Glover and Kosower, 1993
 - **Giele, Kilgore** - 3 jet production
Giele, Kilgore, 2000



Fixed-order QCD Simulations

- Vector boson + heavy flavours

- **MCFM** - $p\bar{p} \rightarrow W^\pm g^*(\rightarrow b\bar{b})$

Ellis and Veseli, 1998

- **MCFM** - $p\bar{p} \rightarrow Z b\bar{b}$

JC and Ellis, 2000

- Vector boson + jets

- **DYRAD** - handles vector boson + 0 or 1 jets

Giele, Glover and Kosower, 1993

- **VECBOS** - handles vector boson + up to 3 (Z) or 4 (W) jets **at leading order only**

Berends, Kuijf, Tausk and Giele, 1991

There are also many leading-order options available:

- Numerous Monte Carlo's
- **COMPHEP** - Model \rightarrow Matrix Elements \rightarrow X-sections
- **MADGRAPH** - just matrix elements



MCFM Process List - v. 3.0

Included at NLO

$$p\bar{p} \rightarrow W^{\pm}/Z$$

$$p\bar{p} \rightarrow W^{+} + W^{-}$$

$$p\bar{p} \rightarrow W^{\pm} + Z$$

$$p\bar{p} \rightarrow Z + Z$$

$$p\bar{p} \rightarrow W^{\pm}/Z + H$$

$$p\bar{p} \rightarrow W^{\pm}/Z + 1 \text{ jet}$$

$$p\bar{p} \rightarrow W^{\pm}/Z + g^{*} (\rightarrow b\bar{b})$$

$$“p\bar{p} \rightarrow W + 2 \text{ jets}”$$

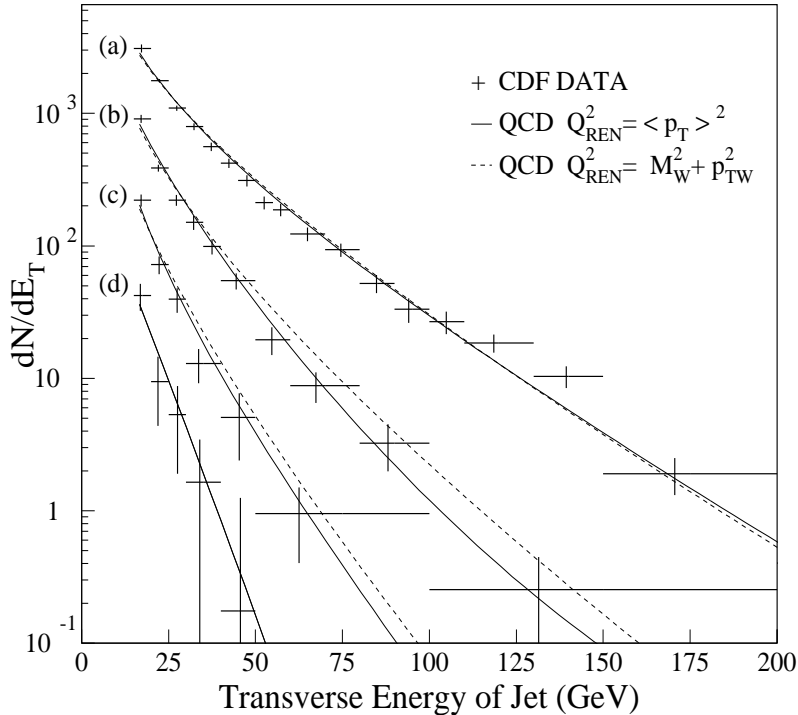
- Various leptonic and/or hadronic decays of the bosons are included as further sub-processes.
- For all processes, agreement between MCFM and other NLO Monte Carlo programs has been obtained, e.g. comparison with DYRAD for $W + 1 \text{ jet}$.
- $W + 2 \text{ jets}$ process is partially implemented at present, more details later.



No NLO prediction for $Z + 2 \text{ jets}$ is yet available, but implementation is in progress and will be completed soon.

Studies using W + jets

- Understanding of QCD (small backgrounds, high Q^2)
 - Inclusive cross-section normalization
 - Jet spectrum
 - Jet algorithms
 - Measurement of α_S



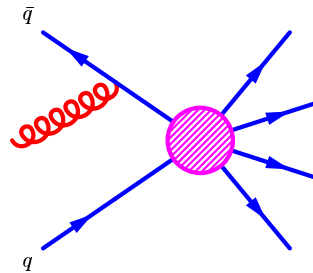
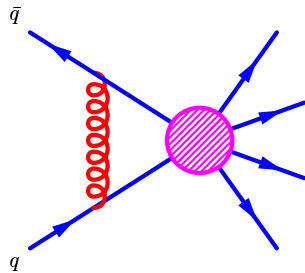
The transverse energy distribution of the n -th highest energy jet in $W + n$ jet events, for CDF data and leading order theory (VECBOS+HERWIG).

- Background for top, SUSY particle, ... production

Monte Carlo Ingredients - 1

- Helicity amplitudes for the virtual and real ME's

m -parton
process



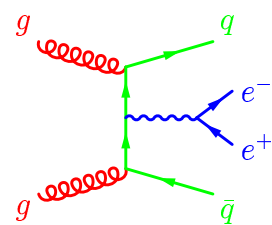
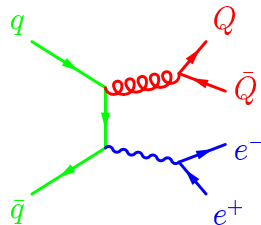
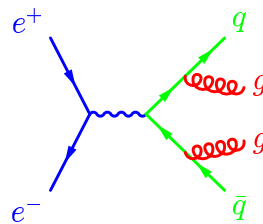
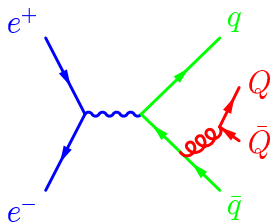
$(m + 1)$ -parton
process

- Many of the NLO matrix elements are obtained by crossing the ones calculated for $e^+e^- \rightarrow 4$ jets.

Bern, Dixon, Kosower and Weinzierl, Nucl. Phys. **B489** (1997) 3

Glover and Miller, Phys. Lett. **B396** (1997) 257

Campbell, Glover and Miller, Phys. Lett. **B409** (1997) 503



Monte Carlo Ingredients - 2

- Singular pieces of the real matrix elements must be identified and cancelled by an appropriate set of counter-terms.
- MCFM uses the **dipole** method to cancel the infrared divergences between real and virtual contributions.

Catani and Seymour, Nucl. Phys. **B485** (1997) 291

$$\begin{aligned}\sigma_{real}^{m+1} &= \int_{(m+1)} (d\sigma_{real} - d\sigma_{counter}) + \int_{(m+1)} d\sigma_{counter} \\ &= (\text{integrable terms}) + \sum_{dipoles} \int_m d\sigma \otimes \int_1 dV_{dipole}\end{aligned}$$

where the 1-dimensional integral over the dipoles leads to soft and collinear divergences (poles in ϵ).

- These poles manifestly multiply m -parton ME's and may be cancelled against poles from the loop diagrams.



Higgs search using MCFM

- Studies using LO Monte Carlos and other event generators show that for a Higgs in the mass range of 100-130 GeV, the most promising channels for discovery at Run II are **associated Higgs production**.

Stange, Marciano, Willenbrock, Phys. Rev. **D49** (1994) 1354, **D50** (1994) 4491

$$p\bar{p} \longrightarrow W(\rightarrow e\nu)H(\rightarrow b\bar{b})$$

$$p\bar{p} \longrightarrow Z(\rightarrow \nu\bar{\nu}, \ell\bar{\ell})H(\rightarrow b\bar{b})$$

- Particularly interesting in the light of hints from LEP2.
- Backgrounds for the WH signal:

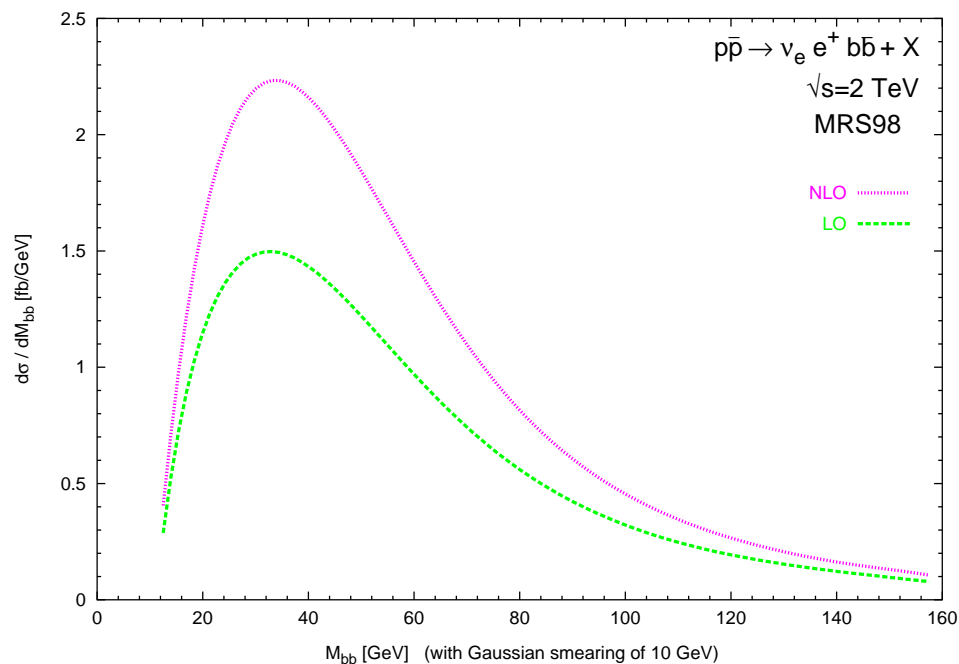
$$\begin{array}{ll} p\bar{p} \longrightarrow W g^*(\rightarrow b\bar{b}) & p\bar{p} \longrightarrow t(\rightarrow bW^+)\bar{t}(\rightarrow \bar{b}W^-) \\ p\bar{p} \longrightarrow W Z/\gamma^*(\rightarrow b\bar{b}) & p\bar{p} \longrightarrow W^{\pm*}(t(\rightarrow bW^+)\bar{b}) \\ & qg \longrightarrow q't(\rightarrow bW^+)\bar{b} \end{array}$$

- The signal, Wg^* and WZ backgrounds are calculable at NLO in MCFM, the remainder at LO. The matrix elements require the approximation $m_b = 0$.



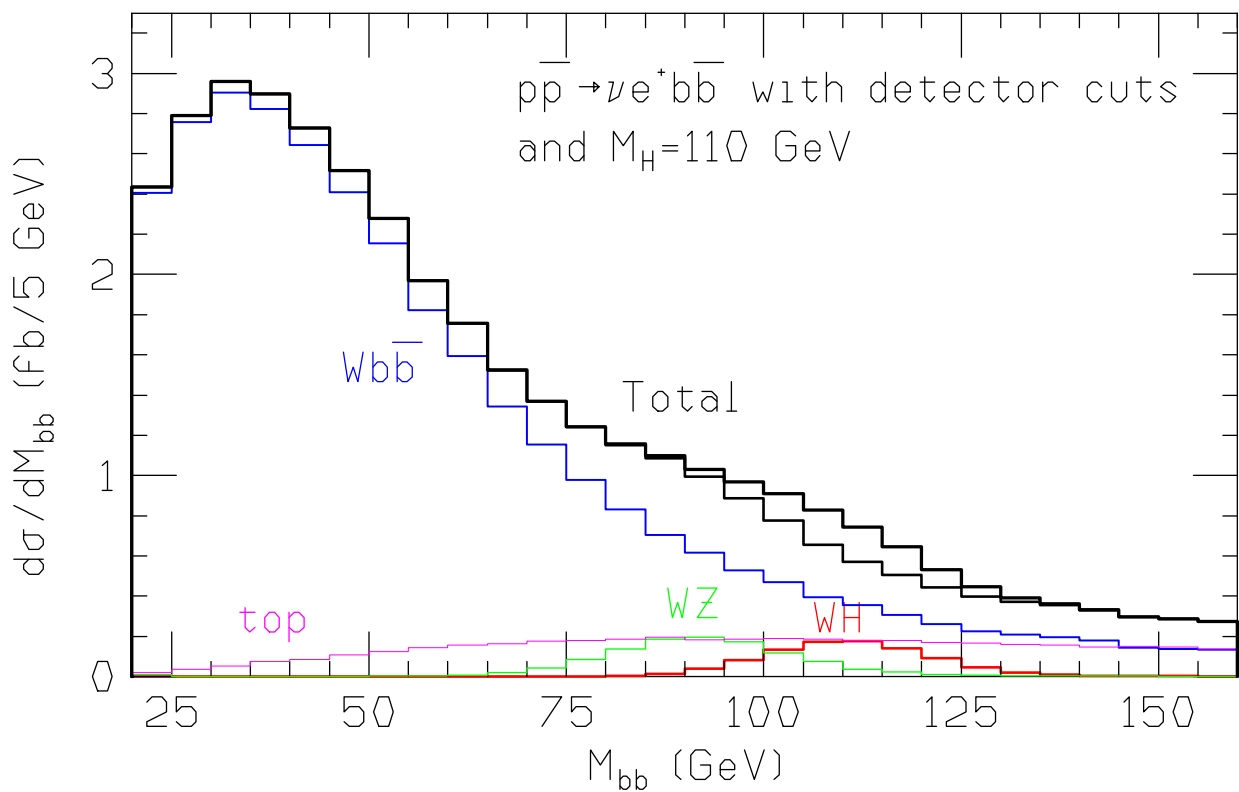
Results for $Wb\bar{b}$

- Use a set of “standard” cuts from the literature, appropriate for the WH study and MRS98 parton distribution functions.
- $m_{b\bar{b}}$ distribution at LO and NLO, scale of 100 GeV.



- The shape changes very little and the “ K -factor” - the ratio of next-to-leading order to leading order - is ≈ 1.5 .

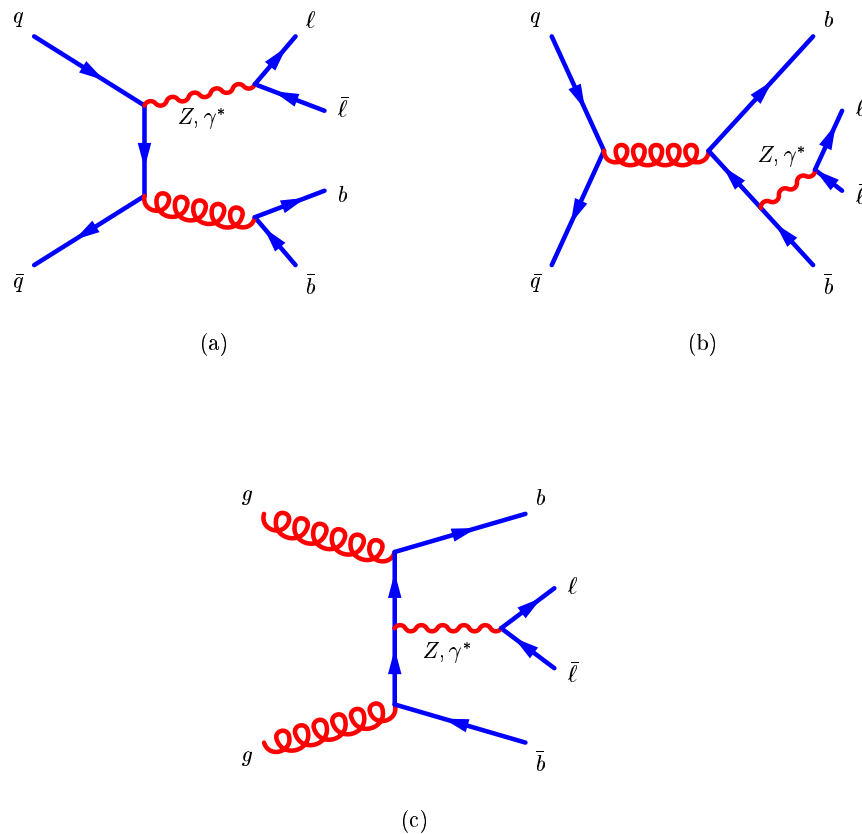
Signal and Backgrounds for $m_H = 110 \text{ GeV}$



- Double b -tagging efficiency of $\epsilon_{b\bar{b}} = 0.45$
- Extraction of the signal requires detailed knowledge of the normalization and the kinematics of the backgrounds.

Results for $Zb\bar{b}$

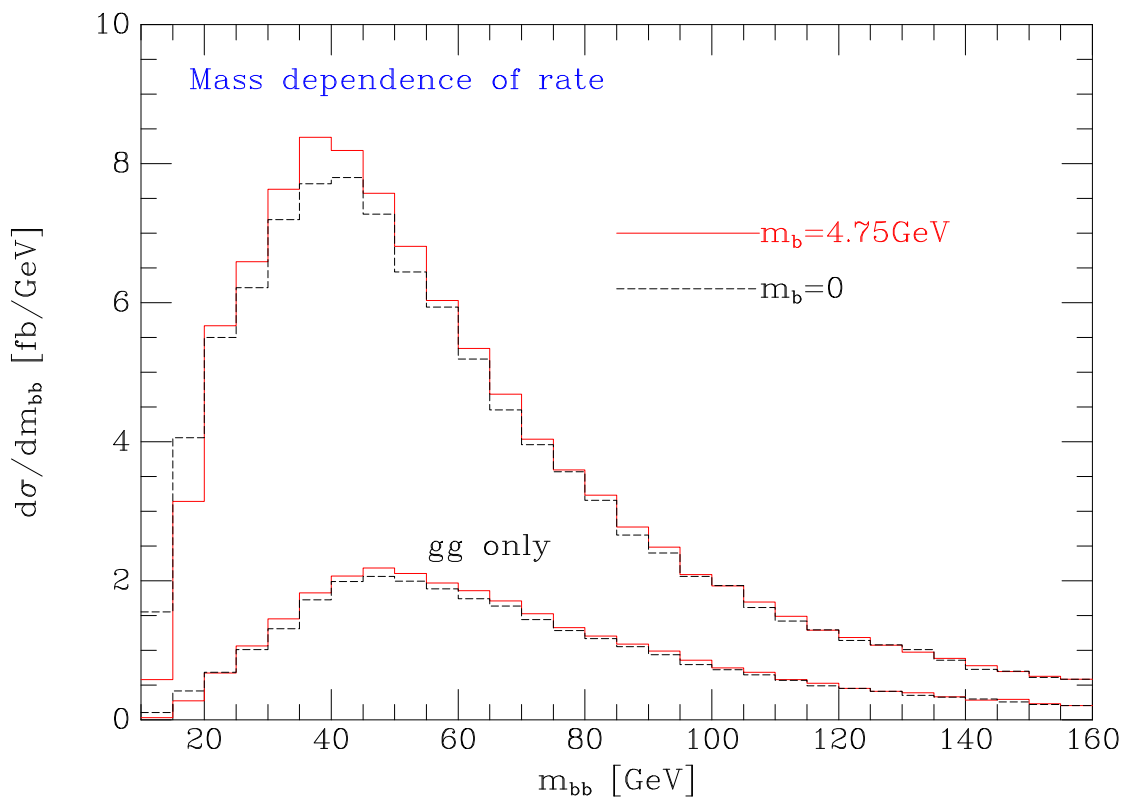
- New results include radiative corrections, relevant for a further Higgs search in the channel ZH .
- The required matrix elements are very similar to the $Wb\bar{b}$ case:



- Diagrams just like $Wb\bar{b}$ (a).
- Two additional types of contribution:
 Z radiating from the $b\bar{b}$ final state (b)
 gg initial state - different matrix elements (c).

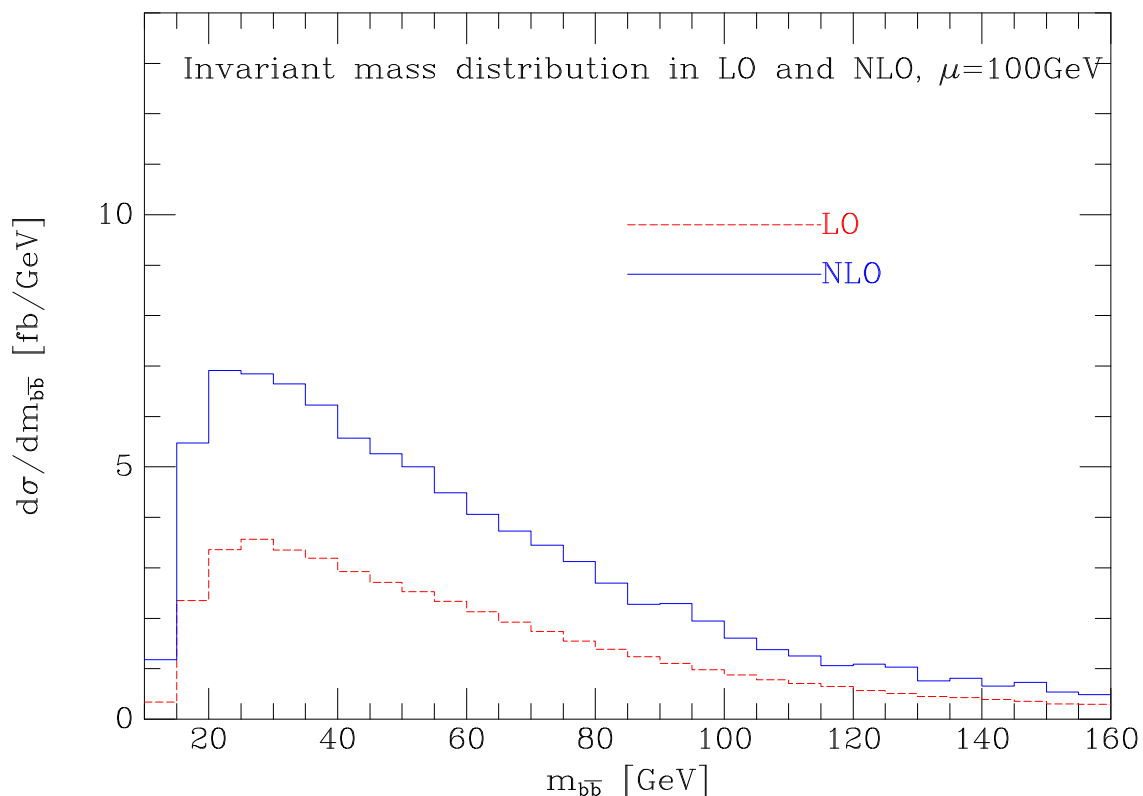
The gg sub-process

- A $b\bar{b}$ pair with a large invariant mass can be produced by the gg initial state process, without off-shell propagators. This gives rise to a large contribution that is important for searches.



$m_{b\bar{b}}$ mass distribution for $Zb\bar{b}$

- For a 'conventional' scale of 100 GeV, there is a large K -factor in the region of interest, around 1.8.

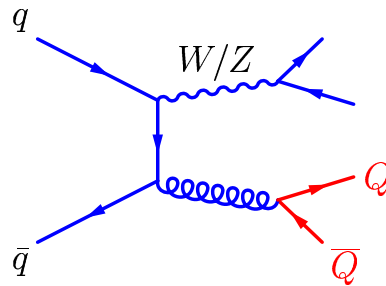


- The entire distribution is changed both in shape and normalization - perhaps suggesting that this scale choice is no longer appropriate (\rightarrow new gg processes).

W + 2 jets: similarities

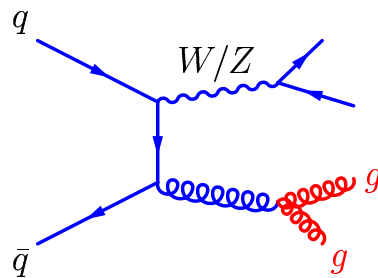
- The $W + 2$ jets process can be viewed as an extension of the already-included $Wb\bar{b}$ and $Zb\bar{b}$ calculations:

- $Wb\bar{b}$ – part of $q\bar{q} \rightarrow W + q'\bar{q}'$



extra diagrams arise
for the case $q = Q$

- $Zb\bar{b}$ – contains $gg \rightarrow Z + q\bar{q}$

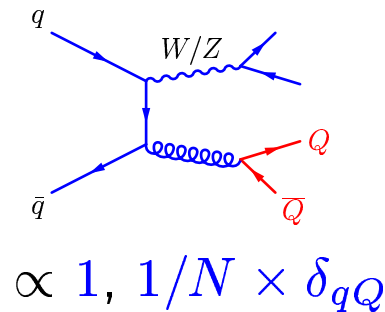
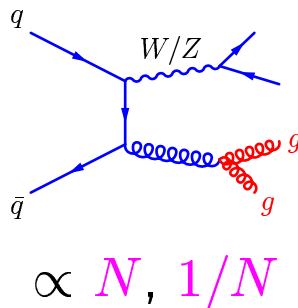


we also need crossings
such as this one

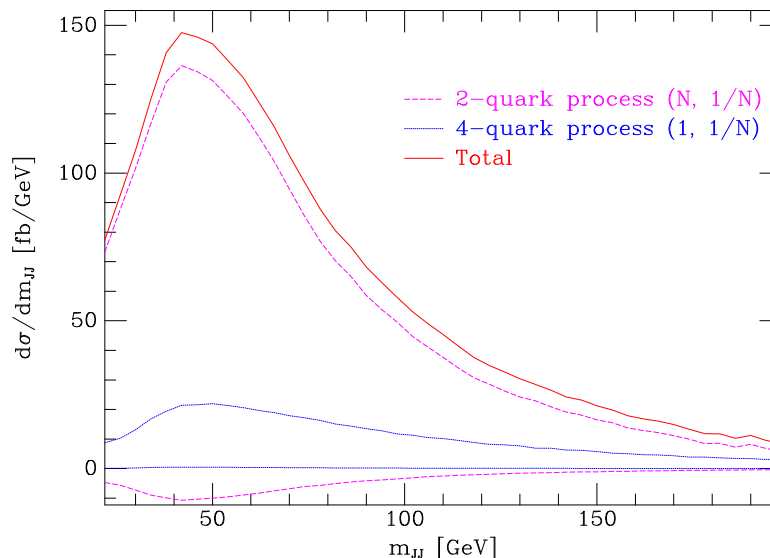
- There are extra parton configurations that we must count, but basically **two sub-processes** – containing either **two** or **four** quarks.
- The contribution from the diagrams that include real radiation must incorporate extra singularities. These are due to more configurations of soft/collinear gluons and, most notably, collinear quark pairs.

W + 2 jets at lowest order

- When calculating the matrix elements, it is possible to separate the diagrams by their colour structure: write in terms of C_A , $C_F \longrightarrow N$.



- With a standard set of cuts, a typical distribution can then be divided into its different colour contributions:



- Leading colour** contribution $\propto N$ really is dominant and a good approximation to the total, both in size and shape.

W + 2 jets at next-to-leading order

- Why bother with a colour decomposition? Let's look at the NLO decomposition for an answer.

- **2-quark** piece:

$$|\mathcal{M}_{NLO}(Vq\bar{q}gg)|^2 \sim \quad \color{red}{1} \quad \longleftarrow \text{Leading colour} \\ + \frac{1}{N^2} \\ + \frac{\color{magenta}{1}}{\color{magenta}{N^4}}$$

- **4-quark** piece:

$$|\mathcal{M}_{NLO}(Vq\bar{q}Q\bar{Q})|^2 \sim \quad \frac{1}{N} \\ + \frac{1}{N^3} \\ + \frac{1}{N^2} \times \delta_{qQ} \quad \longleftarrow \text{(small) identical} \\ + \frac{1}{N^4} \times \delta_{qQ} \quad \text{quark contributions}$$

- One answer: from a book-keeping point of view, constructing the singular counterterms is simpler when broken into colour structures. Different pieces have different poles, e.g. the **“QED” piece** ($1/N^4$) has no gg singularities.
- From this point of view, there is no benefit in the 4-quark matrix elements, so we ignore the colour structure there.



$W + 2 \text{ jets at next-to-leading order}$

Real answer:

- In order to obtain reasonable Monte Carlo integration errors, the running-time must be long. For example, with a Pentium II 400 and a good, optimized compiler:

2-quark real graphs ($1 / \frac{1}{N^2} / \frac{1}{N^4}$) ~ 40 hours

4-quark real graphs (all colours) ~ 55 hours

- The sub-leading virtual matrix elements take significantly longer to calculate:

2-quark virtual graphs: $1 / \frac{1}{N^2} / \frac{1}{N^4}$
 $\sim 6 / 50 / 18$ hours

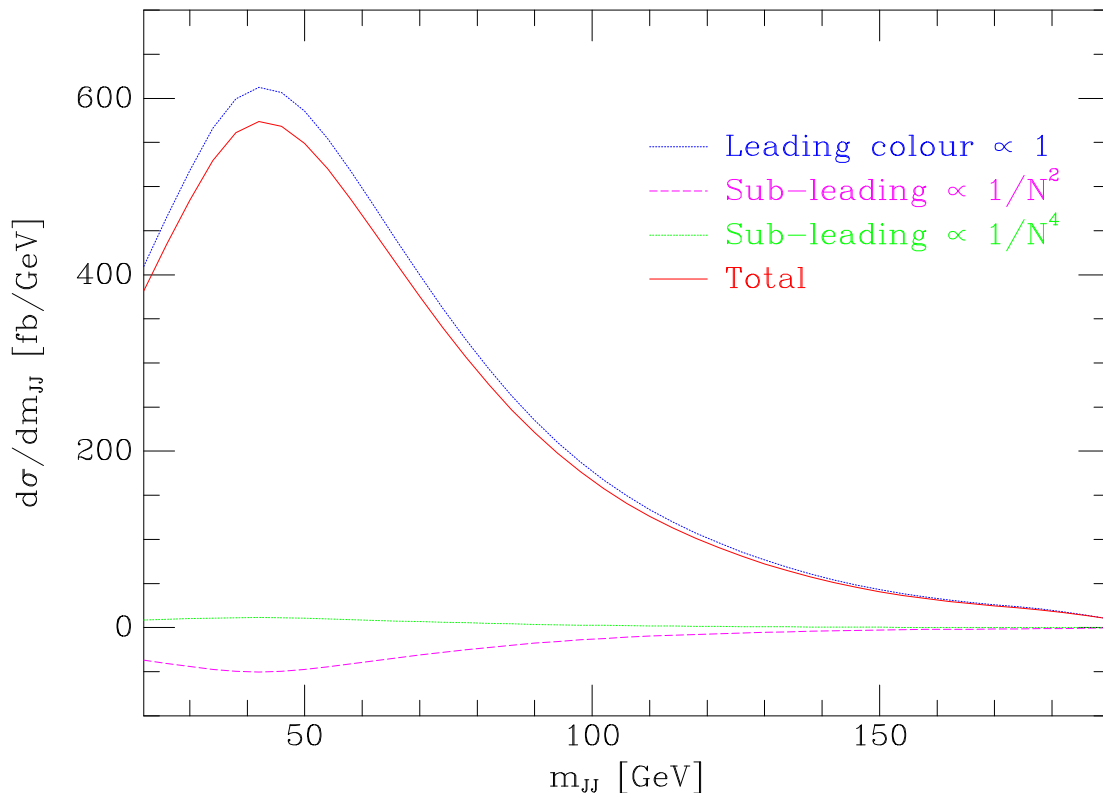
4-quark virtual graphs (all colours)
 ~ 18 hours

- It could be that the sub-leading terms are both **small** and **tedious** to calculate. In this case, a separation by colour structure (at least for preliminary runs) seems worthwhile.
- In particular, we may want the leading colour 2-quark piece plus the 4-quark piece, in order to capture the different sub-process kinematics.



NLO by colour structure

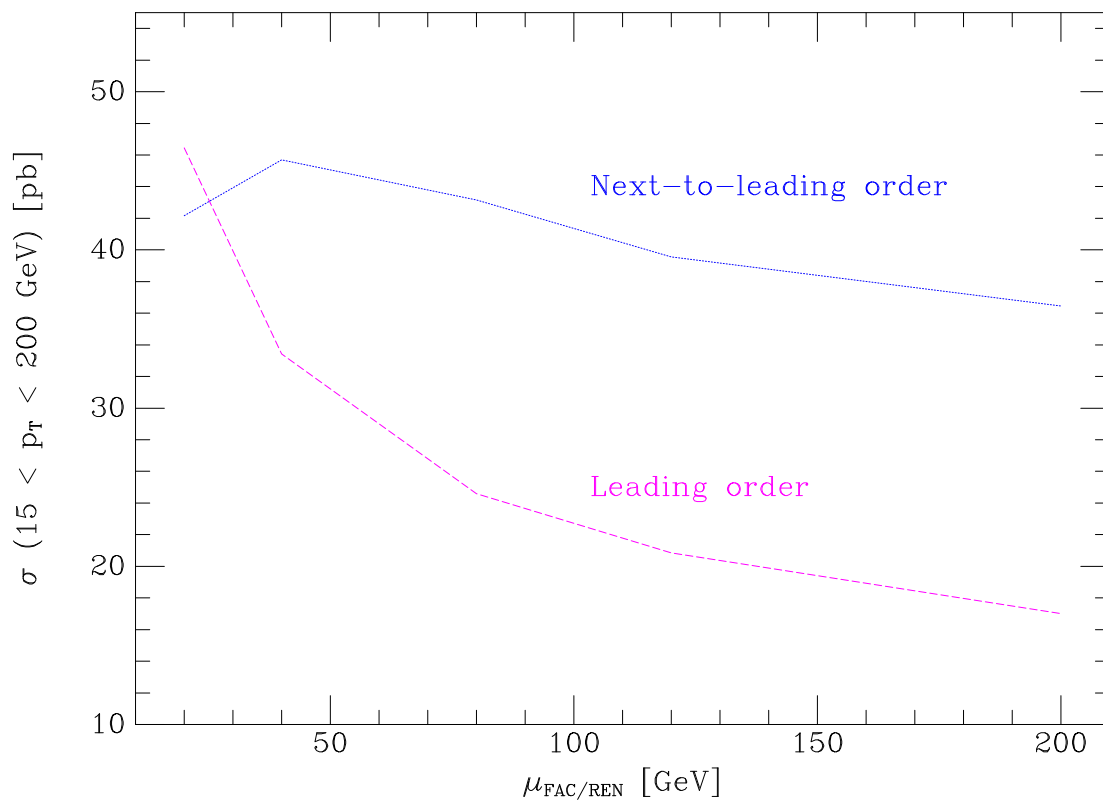
- Typical distribution at NLO, using only the 2-quark matrix elements and separating by colour factors.



- Very similar to leading order, sub-leading pieces are greatly suppressed
 \Rightarrow leading colour is a good and quick approximation.
- 4-quark piece is not yet completely implemented, but will be very soon.

Scale dependence

- An improved (i.e. less sensitive) dependence on the factorization and renormalization scales is expected at NLO - and observed here at leading colour.



- In particular, note the change of normalization between two typical choices of scale, soft ~ 30 and hard ~ 100 GeV:

$$\begin{aligned}\sigma_{LO} (30 \text{ GeV}) &\sim 1.9 \times \sigma_{LO} (100 \text{ GeV}) \\ \sigma_{NLO} (30 \text{ GeV}) &\sim 1.1 \times \sigma_{NLO} (100 \text{ GeV})\end{aligned}$$

Future progress

- Most pressing (and imminent) is the completion of the 4-quark matrix elements
- Extension to $Z + 2$ jets already underway - relatively easy once the W case falls into place.
- Phenomenological studies. Plenty of Run I data at the Tevatron to re-analyze, particularly for the Z . Dialogue with experimenters ongoing.
- Some code optimization may be possible.



Conclusions

- MCFM provides NLO predictions for many femtobarn level processes. Version 2.0 may be downloaded from:
<http://www-theory.fnal.gov/people/campbell/mcfm.html>
- Large radiative corrections to the $Wb\bar{b}$ and $Zb\bar{b}$ processes can significantly change estimates of the backgrounds to the processes $p\bar{p} \rightarrow WH$ and $p\bar{p} \rightarrow ZH$, which will be important search channels at the Tevatron.
- For $W/Z + 2$ jet production, there are two classes of sub-process: 2-quark and 4-quark. The first of these has been implemented in the W case.
- Monte Carlo running-time is long. However, a fast and reliable approximation is provided by the leading colour contribution.
- Full results will be available soon. Many applications, from testing our understanding of QCD to new particle searches.

